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# Influence of the laser source position on the generation of Rayleigh modes in a layer–substrate structure with varying degrees of adhesion

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Non-Destructive Testing of adhesion using Surface Acoustic Waves (SAW) is an important issue in industrial and academic domains. Indeed, these waves are sensitive to the quality of adhesion at the interface between the substrate and the layer with a thickness comparable to the acoustic wavelength. Furthermore, their propagation distance allows a large majority of the sample to be tested quickly. Numerous studies have used SAW for the Non-Destructive Testing of adhesion. However, some recurrent experimental difficulties may lead to an incorrect interpretation of the results. This is the case when the layer thickness is non-uniform, for example. To provide a quasi-constant thickness, a PolyEthylene Terephthalate (PET) film was placed directly on the substrate surface without any glue and Laser-Ultrasonics was used to investigate this type of structure. As the film was transparent at the optical wavelength used, it was possible to focus the laser source on the substrate surface through the film. To the best of our knowledge, no paper has been published on the influence of the source position on adhesion testing. In this work, two source positions were investigated.

**Keywords: Adhesion, Non-Destructive Testing, Surface Acoustic Waves, Laser-Ultrasonics, Wigner-Ville distribution**

## 1. Introduction

Thin films are used in numerous industrial domains such as microelectronics to modify the surface properties of layer-substrate structures. The lifetime of these coatings is directly linked to the quality of adhesion at the interface and so it is very useful to develop a Non-Destructive Testing method to characterize the adhesion.

Surface Acoustic Waves (SAW) are well suited to this purpose. For the structures considered, the SAW become dispersive and are known as Rayleigh modes. The contact conditions at the interface influence this dispersion. Laser-Ultrasonics was chosen for its ability to generate and detect acoustic waves without requiring contact as well as for its large frequency bandwidth [1]–[3].

Numerous studies have been published about adhesion testing using acoustic waves, but many concern bulk waves [4]. Most of the papers dealing with SAW focus on piezoelectric transducers to excite and detect these waves [5], [6]. Only a few deal with laser sources among which a limited

43 number of studies concerns the influence of adhesion on SAW dispersion curves [7]–[15]. Most of  
 44 these studies mention the difficulties in linking the variations in the dispersion to the adhesion due to  
 45 variations in layer thickness [11], [12] and the unknown mechanical characteristics of the glue layer  
 46 [7], [10], [14], [15]. In these studies, only optically opaque samples are considered.

47 To avoid these problems, a PolyEthylene Terephthalate (PET) film was deposited on an  
 48 aluminum substrate. The variations in the thickness of this layer are very small in comparison with  
 49 typical coatings and the film can be stuck to the substrate surface without any glue. Moreover, it is  
 50 optically transparent at the laser wavelength (532 nm), so Rayleigh modes can be generated directly  
 51 on the substrate at the interface by focusing the laser pulse through the film. Consequently, the  
 52 influence of the acoustic source position on the surface waves dispersion according to the variations  
 53 in the degree of adhesion can be investigated.

54 In the first part, we investigate the influence of variations in thickness and adhesion on the  
 55 Rayleigh mode dispersion curves. The Matrix Transfer method by Thomson-Haskell was used to  
 56 establish the dispersion relation [16], [17]. The well known interfacial stiffness method was used to  
 57 model the influence of adhesion on acoustic waves propagation [18]–[20].

58 In the second part, Finite Element simulations taking the position of the source into account are  
 59 presented.

60 Finally, the experimental results are discussed and compared to the theoretical predictions.  
 61 Different degrees of adhesion were considered and their influence on acoustic wave propagation was  
 62 analyzed using a laser source located at the interface.

## 63 2. Analytical study

64 SAW dispersion phenoma depends on the layer and substrate materials, which are assumed to  
 65 be isotropic in this case. Depending on the shear wave velocities of the film and the substrate, it is  
 66 possible to observe three types of dispersive behavior [21]. In our case, the ratio between the shear  
 67 wave velocity in the film  $c_T'$  and in the substrate  $c_T$  is less than  $1/\sqrt{2}$ , as shown in Table 1. In this  
 68 situation, several Rayleigh modes, which the phase velocity decreases with the frequency, propagate  
 69 in the structure. At low frequencies, the first mode tends to the Rayleigh wave velocity in the  
 70 substrate, and higher order modes tend to the shear wave velocity in the substrate because the  
 71 wavelength is long in relation to the film thickness. At high frequencies, the first mode tends to the  
 72 Rayleigh wave velocity in the film and higher order modes tend to the shear wave velocity in the film.  
 73 Indeed, for these frequencies, the acoustic wavelength is small compared to the film thickness [21].

74 These observations are only valid in the case of perfect contact, which is given by:

$$75 \quad \begin{cases} \sigma'_{ij} = \sigma_{ij} \\ u'_i = u_i \end{cases} \quad (1)$$

76 where  $\sigma_{ij}$  is the stress in the substrate at the boundary ( $\sigma'_{ij}$  is the stress in the film at the  
 77 boundary) in the direction  $i$  to the surface of normal  $j$  and  $u_i$  is the particle displacement in the  
 78 substrate at the boundary ( $u'_i$  is the particle displacement in the film at the boundary) in the  
 79 direction  $i$ .

80 The most commonly used model in the literature represents the interface as a very thin layer  
 81 compared to the acoustic wavelength. Adhesion depends on its mechanical characteristics [20]. In  
 82 addition, considering that its mass is negligible, it is possible to approximate the interface with a  
 83 normal and a tangential stiffness, denoted by  $K_n$  and  $K_t$  [20], respectively. The boundary conditions  
 84 are then given as follows:

$$85 \quad \begin{cases} \sigma'_{ij} = \sigma_{ij} \\ \sigma_{ij} = K_m(u'_i - u_i) \end{cases} \quad (2)$$

86 where  $K_m = K_n$  for the normal component to the interface (i.e.  $i = j$ ), and  $K_m = K_t$  for the  
 87 tangential component to the interface (i.e.  $i \neq j$ ).

88 Table 1 summarizes the characteristics used to calculate the dispersion curves presented on  
 89 Figure 1 to 3. These values were measured experimentally using bulk waves generated by  
 90 piezoelectric transducers and the pulse-echo method. The film thickness ( $h = 132 \mu m \pm 1.5 \%$ ) was  
 91 obtained using a high-precision comparator.

	PET film	Aluminum substrate
<b>Longitudinal wave velocity (m/s)</b>	1950	6400
<b>Shear wave velocity (m/s)</b>	1000	3140
<b>Thickness <math>h</math></b>	132 $\mu m$	10 cm
<b>Density (<math>kg/m^3</math>)</b>	1350	2798

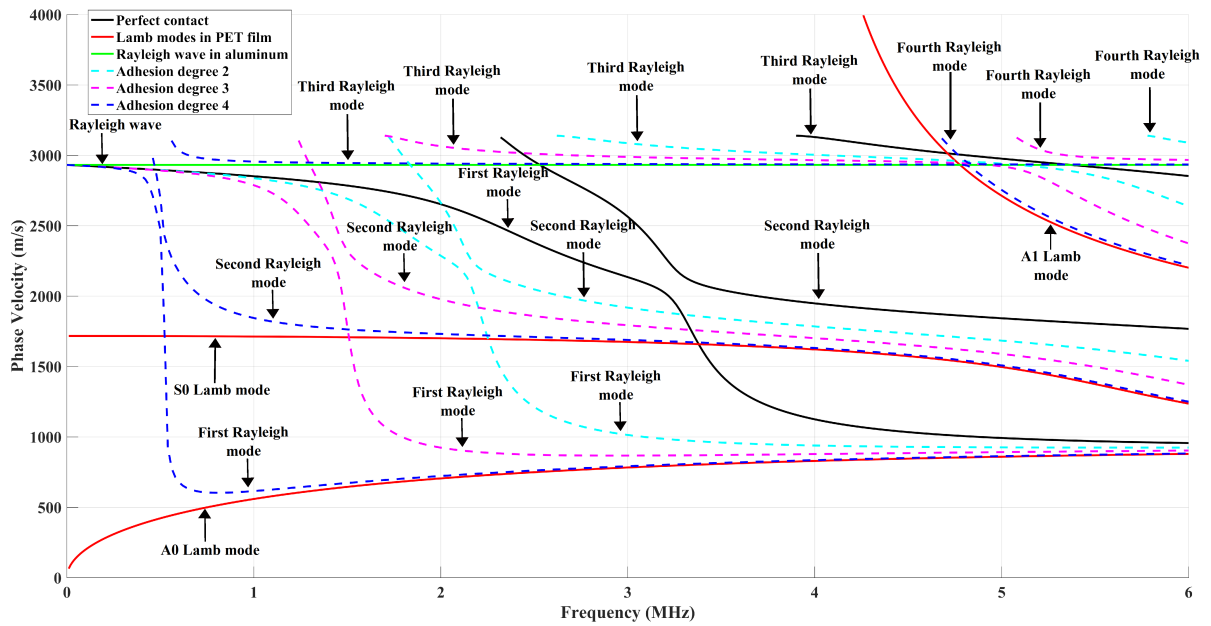
92 Table 1: Characteristics of the materials used for the analytical calculations and the simulations.

93 Table 2 presents the stiffness values used to determine the dispersion curves. The higher  $K_n$  and  
 94  $K_t$ , the greater the adhesion is. Values higher or lower than quasi-perfect contact and quasi-total  
 95 disbanding, respectively, were not considered. Indeed, values outside these limits no longer have a  
 96 significant influence on the dispersion curves. These values were chosen arbitrarily.

Degree of adhesion	Normal stiffness $K_n$ ( $N/m^3$ )	Tangential stiffness $K_t$ ( $N/m^3$ )
Perfect contact	$\infty$	$\infty$
1 (quasi-perfect contact)	$2.10^{16}$	$1.10^{16}$
2	$6.10^{13}$	$3.10^{13}$
3	$2.10^{13}$	$1.10^{13}$
4	$2.10^{12}$	$1.10^{12}$
5 (quasi-total disbanding)	$2.10^8$	$1.10^8$
Total disbanding	0	0

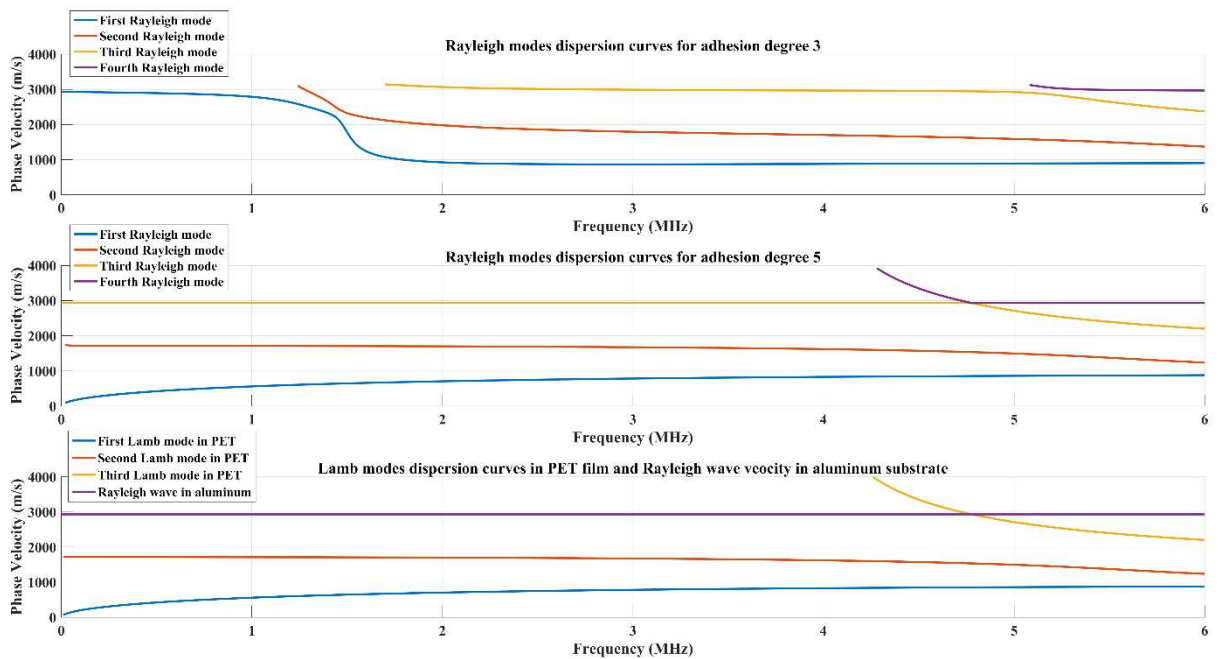
97 Table 2: Stiffness values used to model adhesion for the analytical calculations and the  
 98 simulations.

99 Figure 1 shows the influence of adhesion on the dispersion curves of the Rayleigh modes for a  
 100 PET film on an aluminum substrate structure, calculated using the matrix transfer method [16], [17].  
 101 The dispersion curves corresponding to the degrees of adhesion 1 and 5 overlap with those for  
 102 perfect contact and total disbanding, respectively. The solid lines represent perfect contact (black)  
 103 and total disbanding (green and red). In the latter situation, one curve corresponds to the Rayleigh  
 104 wave propagating in the substrate (green) and the other one to Lamb waves propagating in the film  
 105 (red). The dashed lines represent intermediate degrees of adhesion (2 cyan, 3 magenta and 4 blue).  
 106 The weaker the adhesion is, the more the dispersion curves tend to those for the Rayleigh and Lamb  
 107 waves in the substrate and the film, respectively. In this case, the first two Rayleigh modes clearly  
 108 tend to the first two Lamb modes in the film. With weak degrees of adhesion, the third Rayleigh  
 109 mode tends to the Rayleigh wave in the substrate for the low-frequency part. However, at high  
 110 frequencies, this mode tends to the third Lamb mode in the film. The third and fourth Rayleigh  
 111 modes exhibit the opposite behavior. Figure 2 clearly shows this evolution for the degrees of  
 112 adhesion 3 (top figure) and 5 (middle figure), as well as the Lamb modes in a PET film and the  
 113 Rayleigh wave in an aluminum substrate (bottom figure).



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Figure 1: Rayleigh modes dispersion curves in a PET-aluminum structure for different degrees of adhesion.

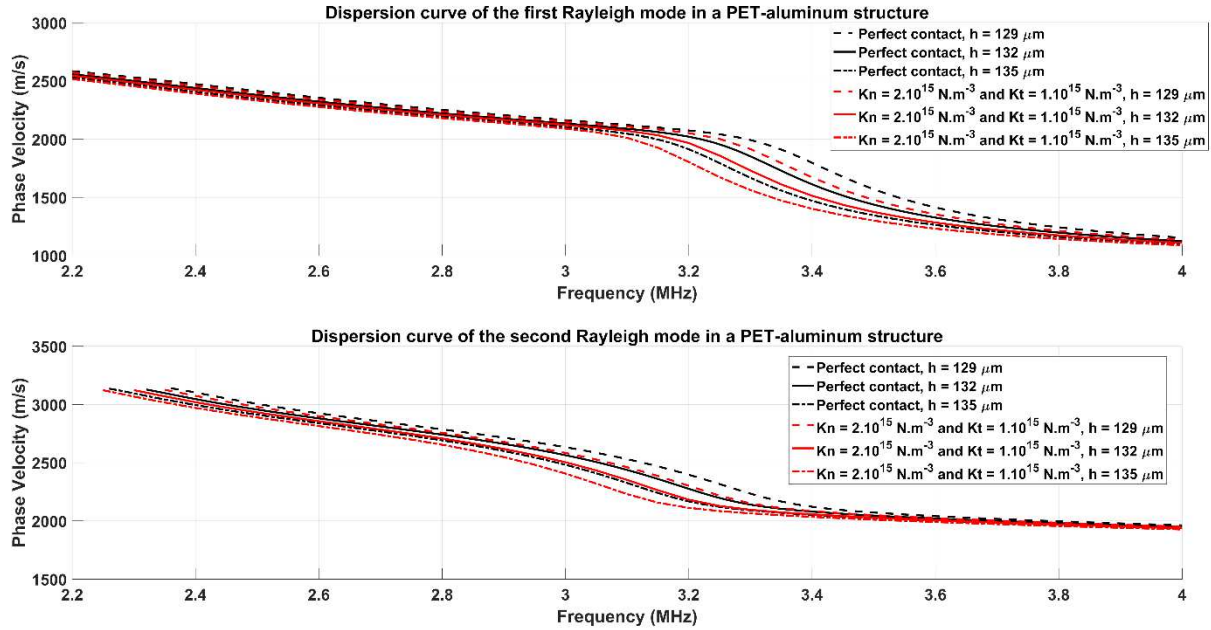


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Figure 2: Rayleigh modes dispersion curves in a PET-aluminum structure for degree of adhesion 3 (top figure), degree of adhesion 5 (middle figure) and Lamb modes in PET film and Rayleigh wave velocity in an aluminum substrate (bottom figure).

121 This result is original because it brings an additional contribution to articles published  
122 concerning the evolution of Rayleigh modes towards Lamb waves in the film [5], [14]. The analytical  
123 calculation carried out does not consider the source position. Two types of Rayleigh mode behaviors  
124 were obtained for weak adhesion but only one of these was observed depending on the position of  
125 the source. In the case of poor adhesion, when the source is located in the film or at its surface, the  
126 dispersion curves tend to those of guided waves in the coating, whereas when the acoustic source is  
127 located on the substrate, the Rayleigh modes become a Rayleigh wave.

128 The film thickness also influences the dispersion curves depending on the quality of adhesion.  
 129 Figure 3 presents the dispersion curves of the first two Rayleigh modes for different film thicknesses  
 130 and contact conditions. As shown, the results obtained with small variations in adhesion are similar  
 131 to those obtained with small variations in thickness. In order to avoid this problem, we have chosen a  
 132 layer-substrate structure with a quasi-constant thickness.



133  
 134 Figure 3: Dispersion curves of first (top figure) and second (bottom figure) Rayleigh modes in  
 135 PET–aluminum structure with different values of thickness for the PET film and different degrees of  
 136 adhesion.

### 137 3. Finite Element Modeling

138 To study the influence of the source position, Finite Element simulations were conducted using  
 139 the COMSOL Multiphysics software [3]. The quality of the adhesion between the film and the  
 140 substrate was modeled by considering the interface as a thin layer 100 nm thick. Its mechanical  
 141 characteristics were determined using the stiffness values given in Table 2 [20].

142 The source for generating the acoustic waves was modeled using a tangential forces dipole at  
 143 the film surface or at the interface. The normal displacement of the acoustic waves was measured  
 144 using 201 point probes with an interval of 50 micrometers.

145 Two configurations were investigated. The source and the probes were placed at the film-  
 146 substrate interface (on the substrate surface) in the first configuration (Figure 4 a) and on the film  
 147 surface in the second case (Figure 4 b). For each configuration, simulations were carried out for the 5  
 148 degrees of adhesion summarized in Table 2. The elastic parameters used for the two materials are  
 149 those given in Table 1.

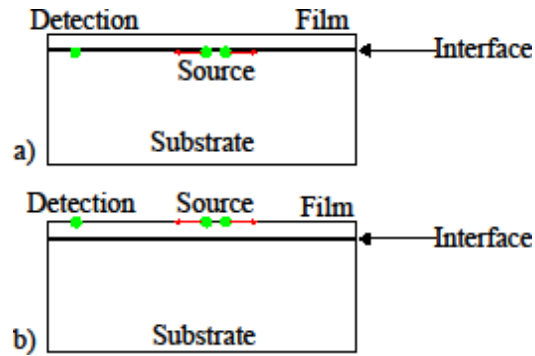


Figure 4: Source and detection positions for the two configurations studied.

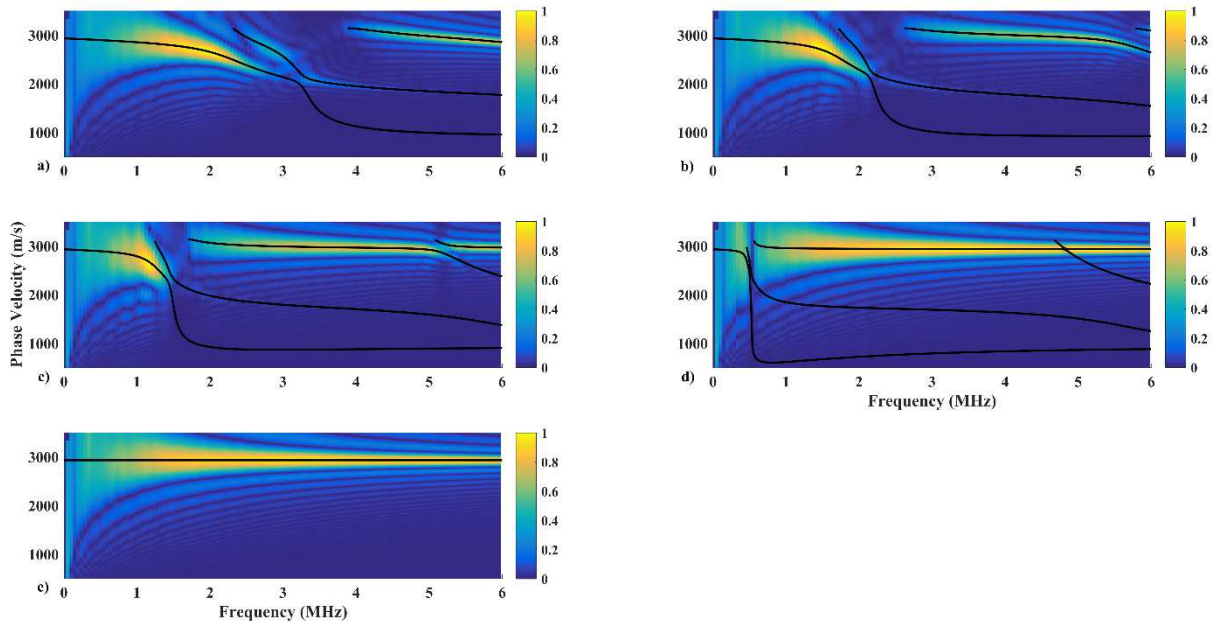
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152 A 2D Fast Fourier Transform was applied to the probe signals to obtain the Rayleigh modes  
153 phase velocity dispersion curves. Figure 5 shows the results for the 5 degrees of adhesion in the first  
154 configuration. The results corresponding to the second configuration are presented in Figure 6. The  
155 colormap corresponds to the normalized modulus of the Fast Fourier Transform. The solid line  
156 represents the previous dispersion curves obtained from the analytical calculations. For the fifth  
157 degree of adhesion, the analytical curves correspond to the Rayleigh wave in the substrate (Figure 5)  
158 and Lamb modes in the film (Figure 6).

159 Figure 5 and 6 clearly highlight the influence of the source position on the modes generated.  
160 When the excitation is at the interface on the substrate side (Figure 5), the first four Rayleigh modes  
161 are clearly observed, as expected. The second mode only appears for very good adhesion and  
162 disappears for bad adhesion. The low-frequency part of the first mode is generated for all degrees of  
163 adhesion except total disbonding. When adhesion decreases, a shift in the dispersion curve to lower-  
164 frequencies is observed. Only the low-frequency part of the third mode and the high-frequency part  
165 of the fourth mode exist for all the degrees of adhesion considered. Whatever the degree of  
166 adhesion, only the parts of the dispersion curves around the Rayleigh wave velocity in the substrate  
167 are generated. This also explains why the second mode is more difficult to excite when adhesion  
168 decreases. Indeed, its part around the Rayleigh wave velocity in the substrate is reduced due to a  
169 steeper slope.

170 When the acoustic source is placed on the film surface, the opposite phenomenon is observed.  
171 This time, the first and second modes are predominant and their excited parts correspond to phase  
172 velocities that are lower or higher than the Rayleigh wave velocity in the substrate. When adhesion  
173 decreases, these modes tend to the first two Lamb modes in the film. The third and fourth Rayleigh  
174 modes are weakly excited with good degrees of adhesion and only the high-frequency part of the  
175 third mode and the low-frequency part of the fourth mode are excited when adhesion is weak. These  
176 two modes merge together to form the third Lamb mode in the film.

177 These results show that each mode is composed of a combination of a Rayleigh wave part and a  
178 Lamb mode part. For a given source position, only one of these two parts is excited. When adhesion  
179 decreases, this part tends to Rayleigh wave in the substrate when the source is placed at the  
180 interface, or tends to Lamb modes in the film when the source is placed at the surface of the film.  
181 These simulations confirm our assumption stated previously following the analytical calculations.  
182 Only one of the two configurations is observed for a given source location when adhesion is very  
183 weak.



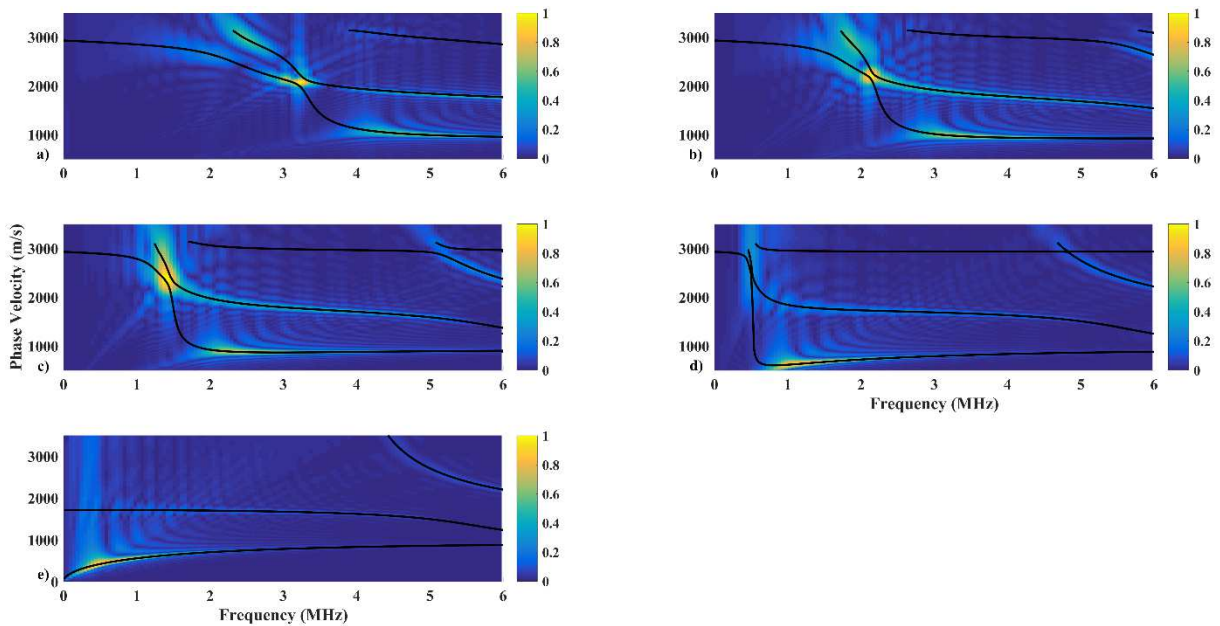
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Figure 5: Dispersion curves obtained from the FEM simulations with source and probes placed between the layer and the substrate at the interface. a) to e): Degrees of adhesion 1 to 5. Black curves correspond to analytical calculations.



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Figure 6: Dispersion curves obtained from the FEM simulations with source and probes placed on the film surface. a) to e): Degrees of adhesion 1 to 5. Black curves correspond to analytical calculations.

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#### 4. Experimental study

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##### a. Measurement setup

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The samples used were composed of a PET film in direct contact with an aluminum substrate. It was possible to remove and replace the film several times before adhesion was no longer possible.

Figure 7 shows the experimental setup. A 10 ns Q-switched Nd:YAG laser pulse of 532 nm was focused as a line source on the aluminum substrate surface, through the PET film.

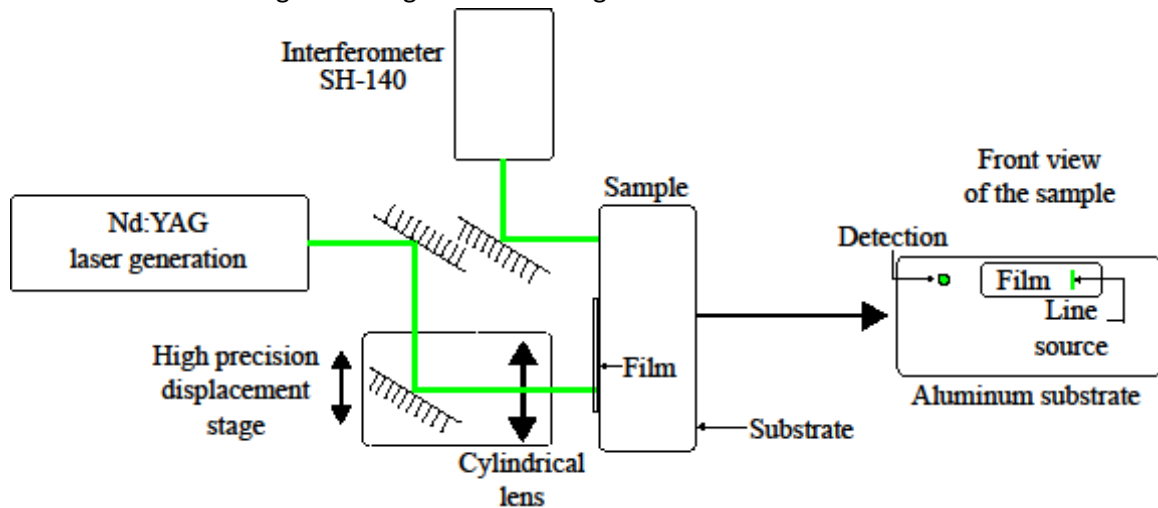


198 The normal displacement of the surface waves was detected by a Mach-Zehnder type  
199 interferometer with a power of 100 mW and a bandwidth of 200 kHz – 45 MHz. To improve  
200 sensitivity, a filter with a bandwidth of 200 kHz – 4 MHz was used. To improve the signal-to-noise  
201 ratio, eight laser shots were performed for each measurement. Detection was achieved directly on  
202 the substrate surface, away from the film.

203 To vary the adhesion, Polytetrafluoroethylene (PTFE) particles were sprayed on the side of the  
204 film in contact with the substrate. These particles are known to be anti-adherent. The film was  
205 removed from the substrate between two experiments to add PTFE in order to progressively  
206 decrease the adhesion. In this way, the variations in surface wave propagation observed  
207 experimentally were mainly due to the contact conditions between the film and the substrate.

208 Four degrees of adhesion were achieved using different grids (see Figure 8) to protect the film to  
209 a lesser or greater extent when the PTFE was sprayed on. The greater the surface area covered with  
210 PTFE, the weaker the adhesion is.

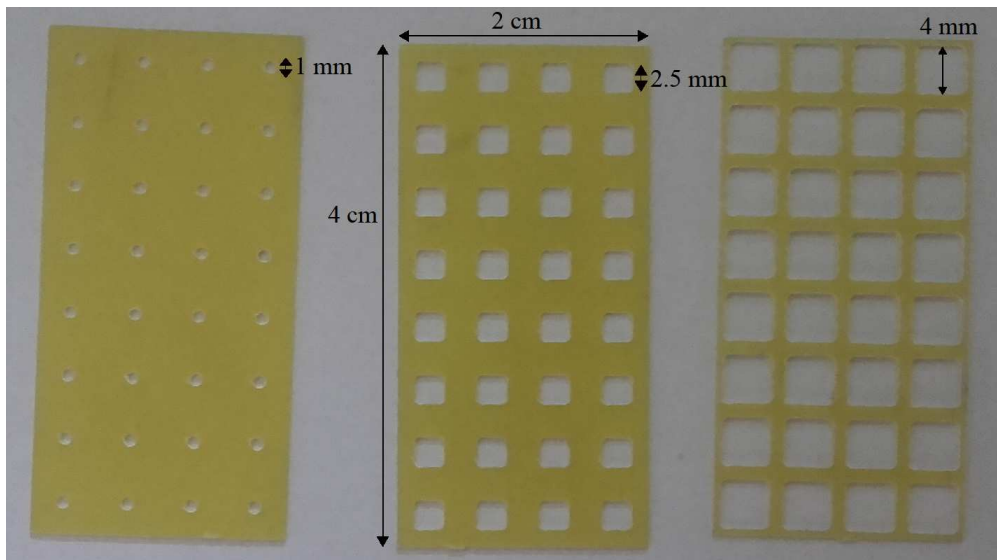
211 The first degree of adhesion corresponds to good adhesion when there is no PTFE on the film.  
212 For the other degrees of adhesion, PTFE was sprayed on the film starting with the grid with the  
213 smallest holes and ending with the grid with the largest holes.



214  
215 Figure 7: Laser-Ultrasonics setup.

216 A smoothed pseudo-Wigner-Ville distribution was applied to the signals obtained, which  
217 provides a good time-frequency representation of the latter [22]–[24].

218 Only the generation and detection at the interface between the substrate and the film was  
219 investigated here. Indeed, the configuration of a source-probe position at the film surface has  
220 already been considered in other studies on opaque films [5].

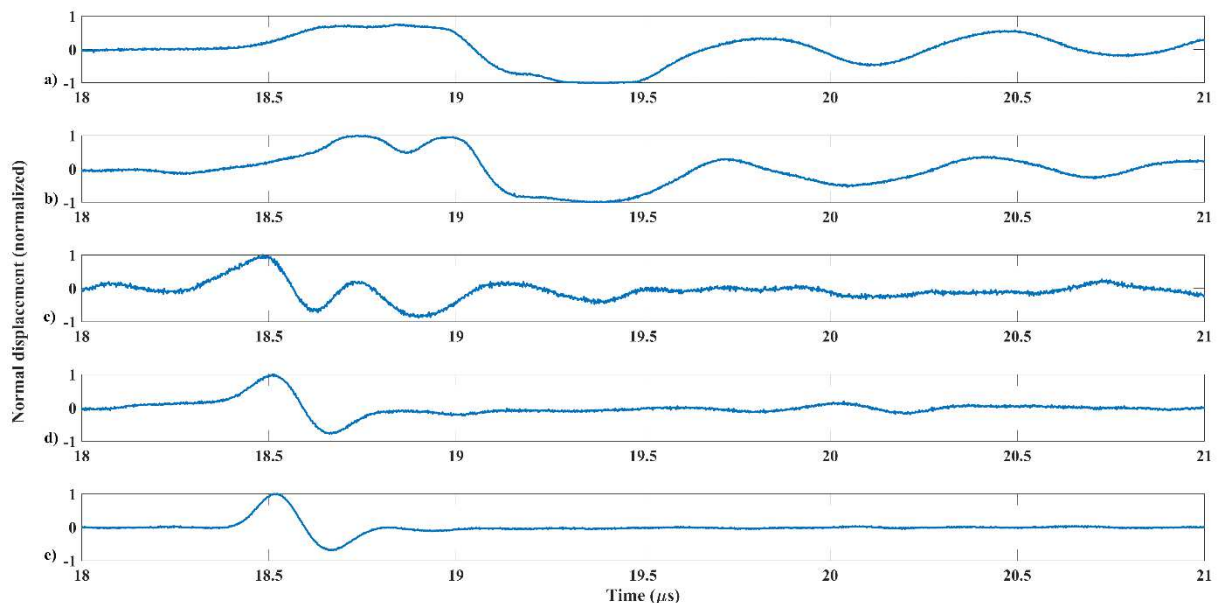


221

222 Figure 8: Grids used to mask the film when the PTFE is sprayed. The left grid allows a weak PTFE  
 223 covering of the surface and the right grid a large one.

224 b. Experimental results

225 Figure 9 presents the signals obtained for the different configurations. Figure 9 a corresponds to  
 226 the signal obtained for the film with no PTFE. Figure 9 b to 9 d correspond to the signals obtained  
 227 with PTFE sprayed through the three grids from left to right, respectively (Figure 8). Figure 9 e was  
 228 obtained for the substrate alone to simulate a total disbonding.



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230 Figure 9: Signals corresponding to the five configurations. a: Without PTFE, b to d: With PTFE  
 231 using grid from left to right (Figure 8), e: Considering substrate without film.

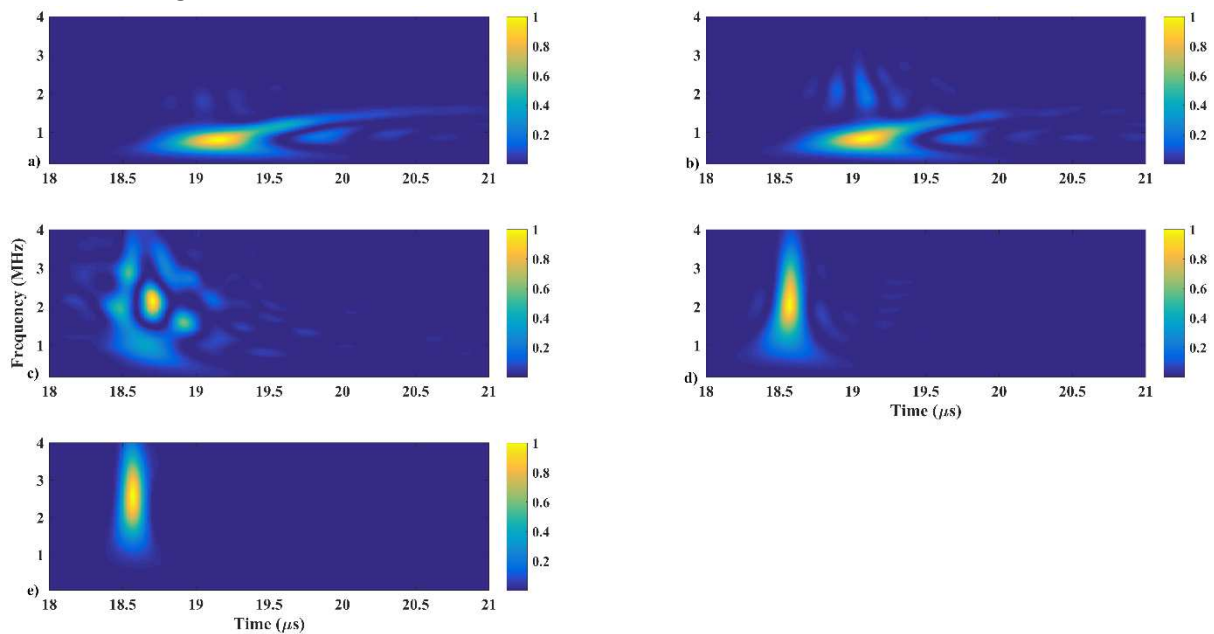
232 Figure 9 clearly shows that the weaker the adhesion, the less dispersive the signal is. With  
 233 complete disbonding the latter becomes a Rayleigh wave in the substrate (Figure 9 e). Figure 9 a and  
 234 9 b are similar due to the small holes in the grid used. The signal in Figure 9 d is very close to the  
 235 Rayleigh wave signal despite the presence of the film over the substrate corresponding to very bad  
 236 adhesion. These results are in good agreement with the simulation results provided previously.

237 Figure 10 presents the smoothed pseudo-Wigner-Ville distributions linked to the signals in  
238 Figure 9. The colormap corresponds to the normalized square modulus of the Wigner-Ville  
239 distribution.

240 As mentioned before, Figures 10 a and 10 b are similar and clearly dispersive. The frequency  
241 band and the dispersive nature of the signals indicate that the first Rayleigh mode is observed, as  
242 shown in Figures 5 a, 5 b or 5 c.

243 Figure 10 d and 10 e exhibit non-dispersive waves as expected from the simulation results in  
244 Figures 5 d or 5 e.

245 Figure 10 c presents a slightly dispersive part at low frequency. Above 1.5 MHz, non-dispersive  
246 components appear at a velocity close to that of the Rayleigh wave. This behavior is similar to that  
247 observed in Figure 5 c.



248

249 Figure 10: Normalized square modulus of the smoothed pseudo-Wigner-Ville distribution for the  
250 signals shown on Figure 9. a: Without PTFE, b to d: With PTFE using grid from left to right (Figure 8),  
251 e: Considering substrate without film.

## 252 5. Conclusion

253 This work deals with the influence of the source position on SAW in film-substrate structures  
254 with varying degrees of adhesion. Analytical calculations, Finite Element simulations, and  
255 experiments were conducted to investigate this. Using a transparent PET film in combination with  
256 Laser-Ultrasonics, we were able to generate acoustic waves at the interface. Furthermore, the small  
257 variations in the thickness of the film made it possible to consider that the changes in Rayleigh  
258 modes behavior were mainly due to adhesion.

259 We have clearly shown that for different degrees of adhesion, the Rayleigh modes behavior  
260 depends on the source position. Two configurations were considered. The first one corresponded to  
261 an excitation located at the interface. In this case, the weaker the adhesion, the closer the Rayleigh  
262 mode behavior was to that of the Rayleigh wave in the substrate. For the second configuration, the  
263 source was placed on the surface of the film. In this case, the Rayleigh modes tended to the Lamb  
264 modes in the film as adhesion decreased.

265 To characterize adhesion, it would be interesting to combine interface excitation with  
266 generation at the surface of the film. This would be very useful to obtain more information and  
267 resolve the inverse problem with greater accuracy.

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